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(71) Applicant: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA [US/US]; Business and Patent Law, Mail Stop D412, Los Alamos, NM 87545 (US).

(71)(72) Applicants and Inventors: EARLY, James, W. [US/US]; 1048 Cedro Court, Los Alamos, NM 87544 (US). LESTER, Charles, S. [US/US]; Route 2, Box 78, San Juan Pueblo, NM 87566 (US).

(74) Agents: BENNETT, Gemma, Morrison et al.; Los Alamos National laboratory, Mail Stop D412, Los Alamos, NM 87545 (US).

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(54) Title: LASER IGNITION

(57) Abstract

In the apparatus of the invention, multiple lasers are used in tandem to provide a compact, durable, engine deployable fuel ignition laser system. Reliable fuel ignition is provided over a wide range of fuel conditions by using a first laser as an excitation light source for one or more small lasers located proximate to one or more fuel combustion zones.

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LASER IGNITION

TECHNICAL FIELD

This invention relates to a method and apparatus for laser ignition.

This invention was made with government support under Contract No. W-7405-ENG-36 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

BACKGROUND ART

Laser light has been used to initiate the ignition of fuel/oxidizer mixtures by use of laser-spark, air-breakdown ignition methods in which a single, high peak power laser light pulse from a Q-switched laser is used to initiate fuel ignition by generating high temperatures and an ionization plasma. These laser ignition methods and apparatuses are generally unreliable except within narrow ranges of fuel parameters such as fuel/oxidizer ratios, fuel droplet size, number density and velocity within a fuel aerosol, and initial fuel and air temperatures.

After initial ignition, sustaining ignition of fuel/oxidizer mixtures is typically accomplished by use of a laser light pulse from a Q-switched laser with a pulse width and pulse energy which will provide the peak power density required to initiate plasma

formation and to satisfy concurrently the need for time-averaged power for sustaining the ignition.

There is still a need for a laser ignition process which can reliably ignite gaseous or aerosol fuel mixtures within a broad range of parameters such as fuel/oxidizer ratios, fuel droplet size, number density and velocity within a fuel aerosol, and initial fuel temperatures as well as a need for means for ignition within small spaces under mechanically adverse conditions.

It is an object of this invention to provide a reliable ignition method and apparatus.

It is another object of this invention to provide a method and apparatus for laser ignition of gaseous or aerosol fuel mixtures within a broad range of parameters such as fuel/oxidizer ratios, fuel droplet size, number density and velocity within a fuel aerosol, and initial fuel temperatures.

It is a further object of this invention to provide a method and apparatus for laser ignition of gaseous or aerosol fuel mixtures within small spaces under mechanically adverse conditions.

It is yet another object of this invention to provide an economical method and apparatus for laser ignition of gaseous or aerosol fuel mixtures.

Additional objects, advantages and novel features of the invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims and is intended to cover all changes and modifications within the spirit and scope thereof.

DISCLOSURE OF INVENTION

To achieve the foregoing and other objects, and in accordance with the purposes of the present invention, as embodied and broadly described herein, there has been invented an apparatus comprising:

(a) an excitation light source laser connected to;

(b) at least one ignitor laser; wherein the excitation light source laser is connected to the ignitor laser so as to permit transport of a first portion of a beam from the excitation light laser into the ignitor laser; and

(c) a beam combiner positioned such that a beam from the ignitor laser is combined with a second portion of a beam from the excitation light laser;

(d) a lens to direct the combined beam from the ignitor laser and second portion of the beam from the excitation light laser into a fuel spray.

There has been an ignition method invented comprising:

(a) splitting a first laser beam from a first laser into at least two portions;

(b) directing a first portion of said first laser beam into a second laser, thereby causing output of a second laser beam;

(c) combining a second portion of said first laser beam with said second laser beam to form a combined laser beam;

(d) directing said combined laser beam into a focal zone within a spray of combustible fuel.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form a part of the specification, illustrate a preferred embodiment of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

Figure 1 is a schematic diagram of a preferred embodiment of the invention.

Figure 2 is a schematic diagram of an alternative embodiment of the invention employing a single ignitor laser pumped by dual excitation pulses.

Figure 3 is a schematic diagram of a multiplexed laser ignition system in accordance with the invention.

Figures 4a and 4b are schematic diagrams of sequential operation of the optical switching system for use of the invention with multiple ignitors.

BEST MODES FOR CARRYING OUT THE INVENTION

It has been discovered that a combination of two or more lasers arranged so that one serves as the excitation light source for one or more small ignitor lasers located more proximately to one or more fuel combustion zones can be used to accomplish durable, reliable, economical ignition of gaseous or aerosol fuel mixtures.

An ignition method which utilizes a combination of short and long duration laser pulse lengths has been invented to provide superior fuel ignition performance relative to conventional laser-based methods with respect to reliability, laser energy efficiency and insensitivity to fuel/air composition and fuel temperatures. The short duration laser pulse generates an air-breakdown plasma, while the longer duration laser pulse sustains the previously generated spark, leading to fuel initiation. Unique laser pulse temporal formats and sequencing are necessary.

An excitation light source laser is used to provide excitation light (low peak power, long duration laser pulse) to one or more small ignitor lasers located more

proximately to one or more fuel combustion zones. The small ignitor lasers provide high peak power short duration laser pulses for the air-breakdown plasma in the fuel aerosol spray or cloud.

The wavelength of laser light useful for the longer duration lower peak power laser pulse from the excitation light source laser is any wavelength in the range from the ultraviolet to the infrared portion of the light spectrum. Wavelengths as short as 200 nanometers can be used effectively for the longer duration lower peak power laser pulse; wavelengths as long as 12 microns can be used effectively for the longer duration lower peak power laser pulse. The excitation source must operate at a wavelength which is absorbed by the laser material utilized as the active lasing medium of the ignitor laser. The excitation source generally is a laser, but may also be a light emitting diode or a flashlamp. Generally, longer wavelengths up to about 12 microns of laser light are preferred due to the greater efficiency in the delivery of laser energy to the plasma generated by the initial short duration laser pulse.

The laser pulse from the excitation laser light source must be of sufficient peak power to efficiently pump the plasma generated by the ignitor laser, but need be of no greater peak power. A peak power of greater than 70 kW is generally sufficient. The temporal length of the laser pulse appropriate for the plasma generation function may be anywhere from 10 or fewer nanoseconds to about 200 nanoseconds in duration,

depending upon the laser pulse energy available. Presently preferred are pulse lengths in the range between about 50 and about 100 nanoseconds, depending upon the laser pulse energy.

The laser pulse from the excitation laser light source may be obtained from any of a variety of laser systems. For example, the excitation laser light may be generated by a Q-switched, cavity dumped or free running laser. The excitation laser can be operated in continuous or pulsed mode. Presently preferred are Q-switched solid-state laser systems. A Q-switched Cr:LiSAF laser is currently preferred because its output can be tuned to a wavelength of 808 nanometers, which is a wavelength that can efficiently pump a Nd:YAG ignitor laser rod. Another good choice for the excitation laser is an Alexandrite laser operating at 750 nanometers, which can also be used to pump the Nd:YAG ignitor laser.

The beam from the excitation light source laser is split, with one portion of the beam directed into the Nd:YAG laser rod of an ignitor laser to provide excitation energy for the ignitor laser which produces long duration laser pulses. A second portion of the beam from the excitation light source laser is used to pump and sustain the breakdown plasma produced by the output of the ignitor laser.

The ignitor laser is a modified laser having a laser rod, optical resonator cavity, and a Q-switch, but little else. The ignitor laser needs no pumping diodes or flashlamps

because it is pumped by laser light coming through at least one fiber optic line from the excitation laser.

It is generally preferred that the ignitor laser be small, i.e., less than a few centimeters in diameter and no more than 20 centimeters in length, because larger sizes would defeat the purposes of having a small, economical, easily positioned ignitor laser which directly replaces the currently used capacitive discharge spark ignitor. The ignitor laser can be simply air-cooled.

The ignitor laser can be composed of any Q-switchable, solid-state laser material which will provide light output within the desired wavelength and peak power range.

Nd:YAG lasers are presently preferred for the ignitor laser due to the inherent high gain properties, lower cost and short duration, Q-switched pulses Nd:YAG lasers can provide. Other useful ignitor laser rod materials include Nd:Glass or Nd:YLF.

The ignitor laser is used to produce laser light having pulse widths in the range from about 1 to about 50 nanoseconds, with pulse energies in the range from about 10 mJ to about 250 mJ being presently preferred.

Which wavelengths from the ignitor laser are most effective depends upon the fuel breakdown processes. Resonant excitation and ionization of the fuel/oxidizer components is typically obtained by utilizing short light wavelengths which are preferred due to the greater efficiency in the ionization yield. For non-resonant ionization of

fuel/oxidizer components, wavelengths as short as 200 nanometers can possibly be effectively used; wavelengths as long as 12 microns can possibly be effectively used. Generally presently preferred for most common fuels are wavelengths in the infrared range from about 700 nanometers to about 12 microns.

The second portion of the beam from the excitation light source laser is directed through a fiber optic line long enough to delay the beam from about 50 to 100 nanoseconds, then through a short focal length lens into a beam combiner where it is combined with the beam from the ignitor laser. The combined beams are directed into a spray or aerosol cloud of the fuel to be ignited.

The temporal length of the long duration lower peak power laser pulse from the excitation laser light source is at least as large or larger than that of the short duration higher peak power laser pulse from the ignitor laser.

In an example of a presently preferred embodiment of the invention, the lasers can be arranged as shown in the schematic diagram of Figure 1. With reference to Figure 1, an excitation light source laser 10 having a Cr:Li:SAF (chromium-doped, lithium-strontium-aluminum fluoride) rod is operated at a wavelength of 808 nanometers to produce laser light pulses with a pulse energy of about 250 mJ. The excitation light source laser 10 is pumped by either flashlamps or light emitting diodes. The excitation

light source laser 10 is operated in a Q-switched mode to produce a short duration (for example, about 100 nanosecond) light pulse at the output of the laser.

The Q-switched light output from the excitation source light laser 10 is directed into a beam splitter 70.

The output of the excitation light source laser 10 is split into at least two beams by the beam splitter 70. A first portion of the output which is split is directed through a lens 80 and is injected into a first multiple-mode optical fiber 130. In this example, 400-micron diameter multiple-mode optical fiber is used for the multiple-mode optical fiber 130. The peak power density of the laser light within the multiple-mode optical fiber 130 is more than a factor of 3 below the threshold for optical damage to the fiber.

The excitation light source laser 10 is operated at sufficiently long pulse times to provide excitation energy for the ignitor laser 170 having an Nd:YAG rod 180. Generally, temporal pulse lengths of about 10 to about 200 nanoseconds are useful in the dual role in which the light from the excitation light source laser is used (to provide excitation of the ignitor laser and to energize the plasma produced in the fuel by light from the ignitor laser). In this embodiment of the invention, the long duration pulses from the excitation light source laser 10 generally have a pulse energy of about 125 mJ and a temporal pulse length from about 50 to about 100 nanoseconds.

The first portion of the laser light from the excitation light source laser 10 coming through the first optical fiber 130 is collected and focused by a lens 160 into the Nd:YAG laser rod 180 of the ignitor laser 170. Laser light at the wavelength (808 nanometers) used in this embodiment of the invention is strongly absorbed within the neodenium-doped YAG lasing material of the ignitor laser and provides the excitation energy required for the ignitor laser 170 to operate.

A lasing condition is quickly established for the ignitor laser cavity within the 100 nanosecond duration of the pump light pulse.

The mirrors for the optical resonator of the ignitor laser 170 consist of high reflectivity dielectric coatings deposited directly upon one end of the laser rod (end facing the excitation light focusing lens 160) and one surface of the Q-switch 190 (surface facing the beam combiner 240). The optical coating placed upon the rod end is highly transmitting of 808 nanometer excitation light although it is highly reflecting to the 1064 nanometer lasing light produced by the ignitor laser 170. The coated end of the laser rod is curved to provide a spherically reflecting cavity end mirror. The coated surface of the Q-switch is optically flat so that, in combination with the spherical mirror at the laser rod end, it forms the resonant cavity within the ignitor laser.

The short duration, Q-switched laser pulse (generally having a duration of about 10 to 15 nanoseconds) generated by the ignitor laser 170 is provided by a passive, solid-state, saturable absorber which is contained within the resonator of the ignitor laser 170.

The pulse energy at the output of the ignitor laser 170 is calculated to be about 80 mJ.

A second portion of the laser light from the excitation light source laser 10 which goes into the beam splitter 70 is reflected by a reflecting mirror 90 which directs the beam through a lens 100 which focuses the beam into a fiber optic delay line 120. In this embodiment, 400-micron diameter multiple-mode optical fiber is also used for the fiber optic delay line 120. The fiber optic delay line 120 is sufficiently longer than the first multiple-mode optical fiber 130 to provide a temporal delay of a number of nanoseconds in the arrival of the second portion of the output of the excitation light source laser 10 beam at a beam combiner 240 beyond the ignitor laser 170. For example, a delay of approximately 50 nanoseconds can usually be accomplished by having the fiber optic delay line 120 about 35 feet longer than the first multiple-mode optical fiber 130. Other methods for introducing a temporal delay between these two pulses, including the use of reflective or diffractive multiple pass delay lines, can effectively serve the same role.

Laser light from the fiber optic delay line 120 is collimated using a short focal length lens 220 and then directed by way of a reflecting mirror 230 to a beam combiner

240 where it is spatially overlapped and co-axially propagated with the light output of the ignitor laser 170, although it is delayed by a number of nanoseconds relative to the output of the ignitor laser 170. Generally a delay of about 25 to about 150 nanoseconds is most useful, depending upon the properties of the fuel to be ignited.

Laser light from the beam combiner 240 having both long and short duration laser pulses from the excitation light source laser 10 and the ignitor laser 170, respectively, is then directed to a common lens 250 in which both laser pulses are focused through a laser window 260 to a preselected position or focal point 270 within the fuel spray 280 from a fuel nozzle 290 in the combustion zone. A common lens having a short focal length is generally preferred because of the high laser light power density achieved although multiple focusing elements can be used effectively. For example, a 10 cm focal length lens is found to be useful for the generation of an air breakdown spark and efficient coupling of second pulse light from the second portion of the laser light from the excitation laser light source 10 to the breakdown plasma.

A spark breakdown plasma in the fuel spray 280 is formed by the output of the ignitor laser 170 followed by the sustenance of the plasma by the long duration pulse from the second portion of the beam from the excitation light source laser 10. Thus, an effective dual pulse of laser light within the temporal format required to achieve optimal fuel ignition performance is provided.

The two portions into which the beam from the excitation light source laser 10 is split are generally of the same intensity. Approximately 125 mJ of excitation laser light is required to pump the ignitor laser sufficiently to produce 80 mJ in the output pulse of the ignitor laser and also 125 mJ of excitation laser light is required to effectively energize the breakdown plasma spark produced by the ignitor light.

The ignitor laser can have a lasing crystal as small as 1 centimeter in length and a resonant cavity as small as about 6 centimeters in length. The ignitor laser requires no electrical power input, no laser pumping elements such as flash lamps and light emitting diodes, no electro-optical devices and requires no circulated water cooling (can be air cooled). However, water cooling may be utilized as desired or needed for high ignition laser pulses rates.

The small physical size of the ignitor laser (generally about 2 cm in diameter and 10 cm in length) as well as the simplicity of the laser design permits placement of the ignitor laser proximate to the fuel spray of a combustor of a turbojet engine or other type engine (such as diesel).

In another embodiment of the invention, the manner in which the ignitor laser is pumped can be altered to produce two sequential pulses which conform to the required dual pulse fuel ignition format, thus eliminating the need for a beam combiner between the small ignitor laser and the combustion zone. In this second embodiment, shown in

the schematic of Figure 2, the excitation light 50 from the excitation laser light source 10 is split into two beams by a beam splitter 70. A first portion is focused by a lens 80 and injected into a first optical transport fiber 130. A second portion of the excitation light from the beam splitter 70 is reflected by a mirror 90 and lens 100 into a fiber optic delay line 120. As in the first described embodiment of the invention, the fiber optic delay line 120 is longer than the first multiple-mode optical fiber 130 in order to provide a temporal delay in the delivery of a portion of the excitation light to the ignitor laser 170.

In this second embodiment, and still with reference to Figure 2, the light output of the two optical fibers is recombined using an optical fiber coupler 150 which couples both beams into a single fiber 155 which carries the two excitation light pulses through a focusing lens 160 to the ignitor laser rod 180. The first excitation pulse quickly establishes a lasing condition in the laser rod 180 which results in the formation of a short duration pulse (generally from about 10 to about 15 nanoseconds) in the output of the ignitor laser 170 by the action of the saturable absorber, Q-switch 190. Before the bleached Q-switch can recover (re-set), the arrival of the second excitation pulse re-establishes a lasing condition in the laser rod 180 which results in the formation of a gain-switched light pulse in the output of the ignitor laser 170. The pulse width of the gain-switched pulse is approximately equal to that of the excitation pulse (generally about 100 nanoseconds). In this manner, two sequential laser pulses with high and low peak powers

are generated and separated in time by the temporal delay between the excitation pulses. Both laser pulses from the ignitor laser 170 are focused within the fuel by a common lens 250.

Alternatively, a single multiple-mode optical fiber 130 can be used to transport excitation light from the excitation laser light source 10 to the ignitor laser 170 without use of the optical delay line 120. The pulse length of the excitation laser light can be longer (generally up to 1 microsecond) because the excitation laser light source 10 is used only to generate single pulses of short duration laser light at the output of the ignitor laser 170 and is not additionally focused into the fuel spray.

The temporally delayed excitation pulses transported to the ignitor laser may be multiplexed to several ignitor lasers in a manner similar to that described for the embodiment of the invention using fiber pair switching.

More than one ignitor laser can be used with a single excitation light source laser. This configuration is desirable for applications in which multiple ignitors are required for each engine combustion chamber or where multiple combustion chambers or engines are used. The smaller ignition lasers could be placed proximate to the fuel jets for each of the cylinders and a single remote excitation light source laser used to power the smaller ignition lasers. The smaller, low-cost ignition lasers with no pumping elements such as flashlamps or diode lasers, and with no electro-optic devices can be built to tolerate the

extreme temperature variations and vibrations in the engine operating environment while the more expensive, more fragile excitation light source laser is safely positioned in the fuselage of the aircraft.

The capability of multiplexing an excitation light from the excitation light source laser with several different ignitor lasers reduces the cost that would be associated with having to have two excitation light producing lasers at each of the combustion chambers of an aircraft and the cost that would be associated with maintenance of fragile, temperature sensitive and expensive excitation sources, such as flashlamps or diode lasers in the extreme environments of combustion chambers.

To achieve this multiplexing function, an optical switching system is used to sequentially direct excitation light from the single excitation laser into multiple pairs of optical fibers, of which each pair is connected to an individual ignitor laser.

A schematic of a multiplexed arrangement of the lasers in a third embodiment of the invention is shown in Figure 3. With reference to Figure 3, a excitation laser 10 is used to provide low peak power, long duration pulse light light energy for several ignitor lasers. The excitation laser light 50 is directed into a means for optical switching of the excitation laser light beam 50 sequentially from one pair of optical fibers 122 and 132 to another 124 and 134, and to as many other pairs of optical fibers as are used in turn.

A simple and economical optical switch which can be used in this multiplexed embodiment of the invention is based upon a rotatable 90-degree prism 64 as shown in Figures 4a and 4b. With reference to Figure 4a, excitation light is directed into the lower (bottom) face of the prism 64 where it is reflected through a 90° angle. Excitation light exiting the prism 64 is then directed to a beam splitter 70 where the excitation laser light is split into two equal intensity beams. The two beams are then injected into two optic fibers 122 and 132 transporting the excitation light to a single ignitor laser in a manner identical to that described for the first and second embodiments of the invention having a first multiple-mode optical fiber and a fiber optic delay line transporting excitation light in sequential pulses to an ignitor laser.

To excite a second ignitor laser, the prism 64 is rotated to an angular position so that the excitation light is directed to a second beam splitter 72 which then directs excitation light to a second pair of optical fibers 124 and 134 transporting excitation light to the second ignitor laser. This second position of the prism 64 is shown in Figure 4b.

Likewise, third, fourth, and more ignitor lasers can be powered by the single excitation laser light source 10, by rotating the prism 64 through more angles to direct laser light through other beam splitters into other pairs of optical fibers that take sequential pulses of laser light to the ignitor lasers in sequential turn. In this manner,

numerous remotely located ignitor lasers can be energized sequentially by a single excitation laser source.

In another alternative device and method, similar switching action can be performed in an apparatus using only the multiple-mode optical fiber and no fiber optic delay line; i.e., only one fiber is used to link the excitation source with the ignitor laser or ignitor lasers.

Although an optical switching means based upon a rotatable prism is described in Figures 4a and 4b, other optical switching systems can be utilized; for example, electro-optic switches perform the same function.

The small physical size and simplicity of design of the ignitor laser enables an effective, compact, robust and cost effective laser ignitor package which is about the same size as the spark plug which it replaces.

While the apparatuses and methods of this invention have been described in detail for the purpose of illustration, the inventive apparatuses and methods are not to be construed as limited thereby. This patent is intended to cover all changes and modifications within the spirit and scope thereof.

INDUSTRIAL APPLICABILITY

The apparatus and method of the invention can be used as an ignition source for turbojet engines, internal combustion engines, diesel engines and gas turbines, for electrical power generation.

WHAT IS CLAIMED IS:

1. An apparatus for fuel ignition comprising:

(a) an excitation light source laser;

(b) a beam splitter positioned to receive laser light from said excitation light source laser;

(c) at least two optical fibers connected to said beam splitter connected so as to receive portions of laser light from said beam splitter, with at least one of said at least two optical fibers being longer than at least one other of said at least two optical fibers;

(d) at least one ignitor laser connected to at least one of said at least two optical fibers opposite said beam splitter;

(e) a lens positioned to direct a laser beam from said at least one ignitor laser into a fuel spray.

2. An apparatus as recited in Claim 1 wherein said apparatus further comprises:

(a) a beam combiner positioned to receive laser light from said ignitor laser and from said at least one of said at least two optical fibers, that being an optical fiber longer than said at least one optical fiber connected to said at least one ignitor laser; and

(b) a lens to direct a combined beam from said beam combiner into a fuel spray.

3. An apparatus as recited in Claim 1 wherein said apparatus further comprises a beam combiner positioned to receive laser light from at least two of said at least two optical fibers and positioned to direct a combined beam into said at least one ignitor laser.

4. An apparatus as recited in Claim 2 further comprising an optical switching means connected to switch beams in each of said at least two optical fibers from said at least one ignitor laser to at least one other said at least one ignitor laser.

5. An apparatus as recited in Claim 3 further comprising an optical switching means to switch a combined beam from said beam combiner from one said at least one ignitor laser to another said at least one ignitor laser.

6. An ignition method comprising:

(a) splitting a first laser beam from an excitation laser into at least two portions;

(b) directing a first portion of said excitation laser beam through a first optical fiber thereby pumping said ignitor laser, causing output of an ignitor laser beam;

(c) directing a second portion of said excitation laser beam through a second optical fiber into a beam combiner;

(d) combining said second portion of said excitation laser beam with said ignitor laser beam to form a combined laser beam;

(e) directing said combined laser beam into a focal zone within a spray of combustible fuel.

7. A method as recited in Claim 6 wherein said second optical fiber delays said second portion of said first laser beam so that said second portion of said first laser beam from said excitation laser arrives at said beam combiner at a later time than said first portion of said first laser beam from said excitation laser.

8. An ignition method comprising:

(a) splitting a first laser beam from a first laser into at least two portions;

(b) directing a first portion of said first laser beam into a first optical fiber;

(c) directing a second portion of said first laser beam into a second optical fiber, said second optical fiber being longer than said first optical fiber;

(d) combining said first portion of said first laser beam with said second portion of said first laser beam to form a combined laser beam having pulses from both said first portion and said second portion of said first laser beam;

(e) directing said combined laser beam into an ignitor laser;

(f) directing output of said ignitor laser into a focal zone within a spray of combustible fuel.

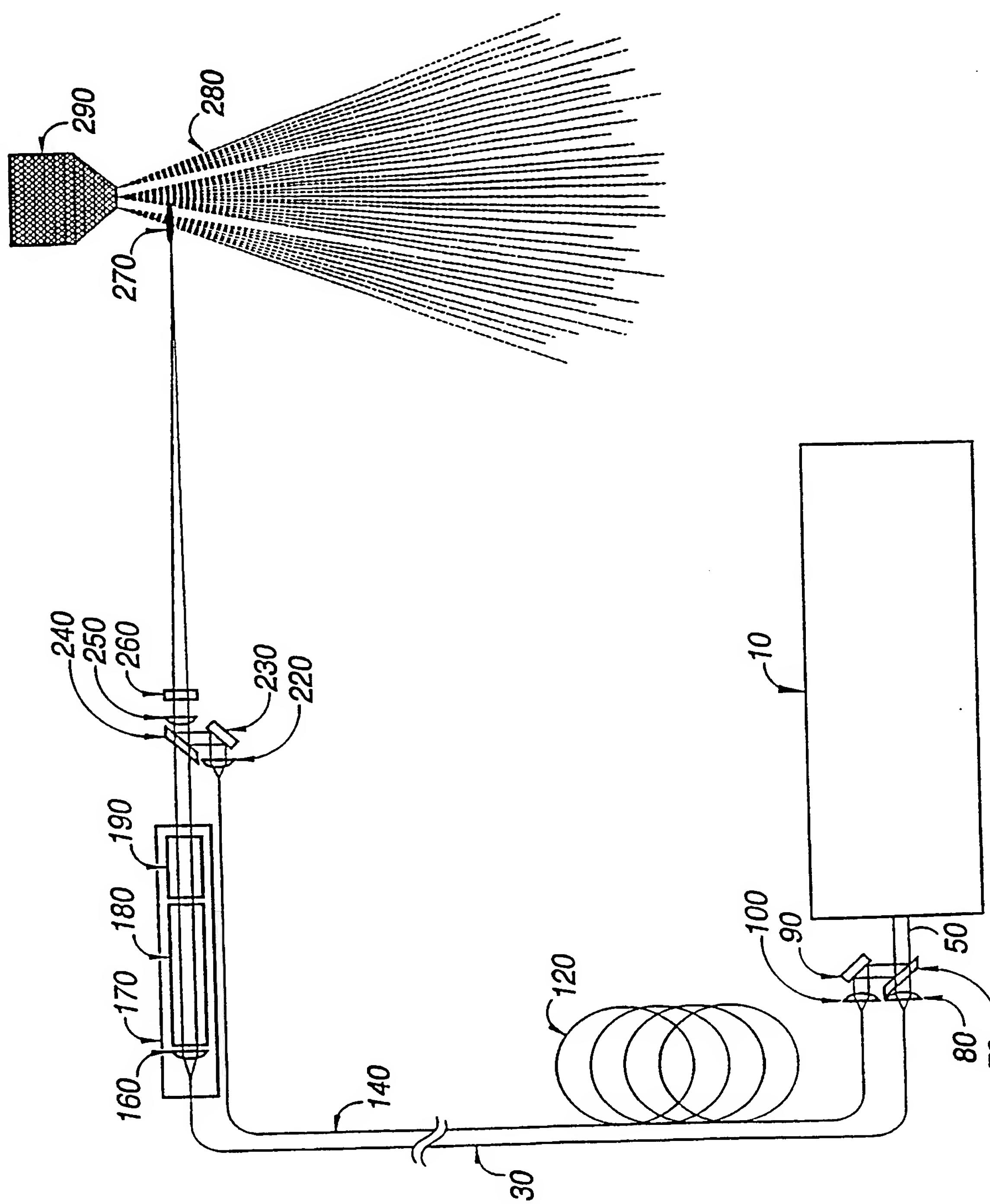
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Fig. 1

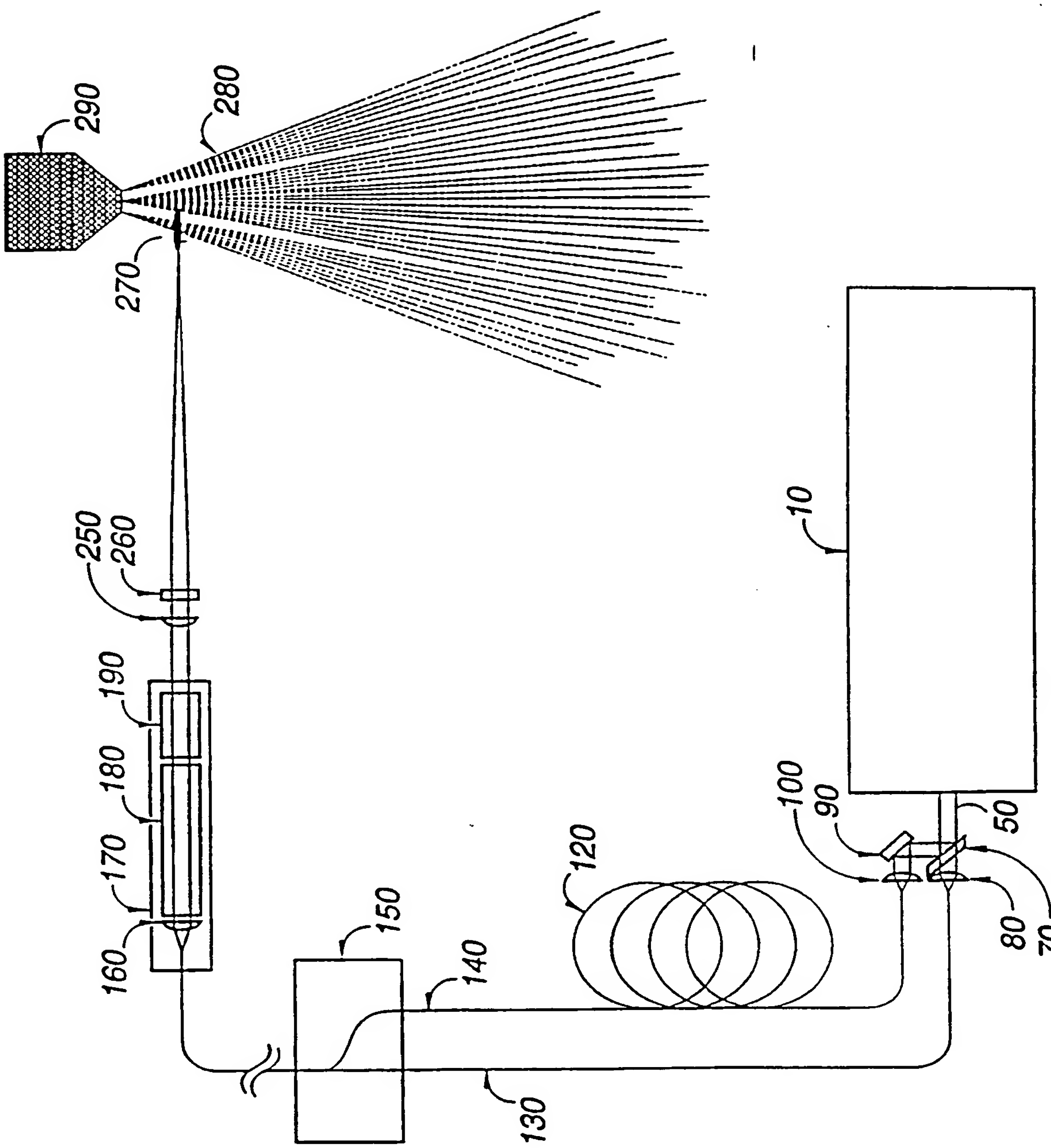
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Fig. 2

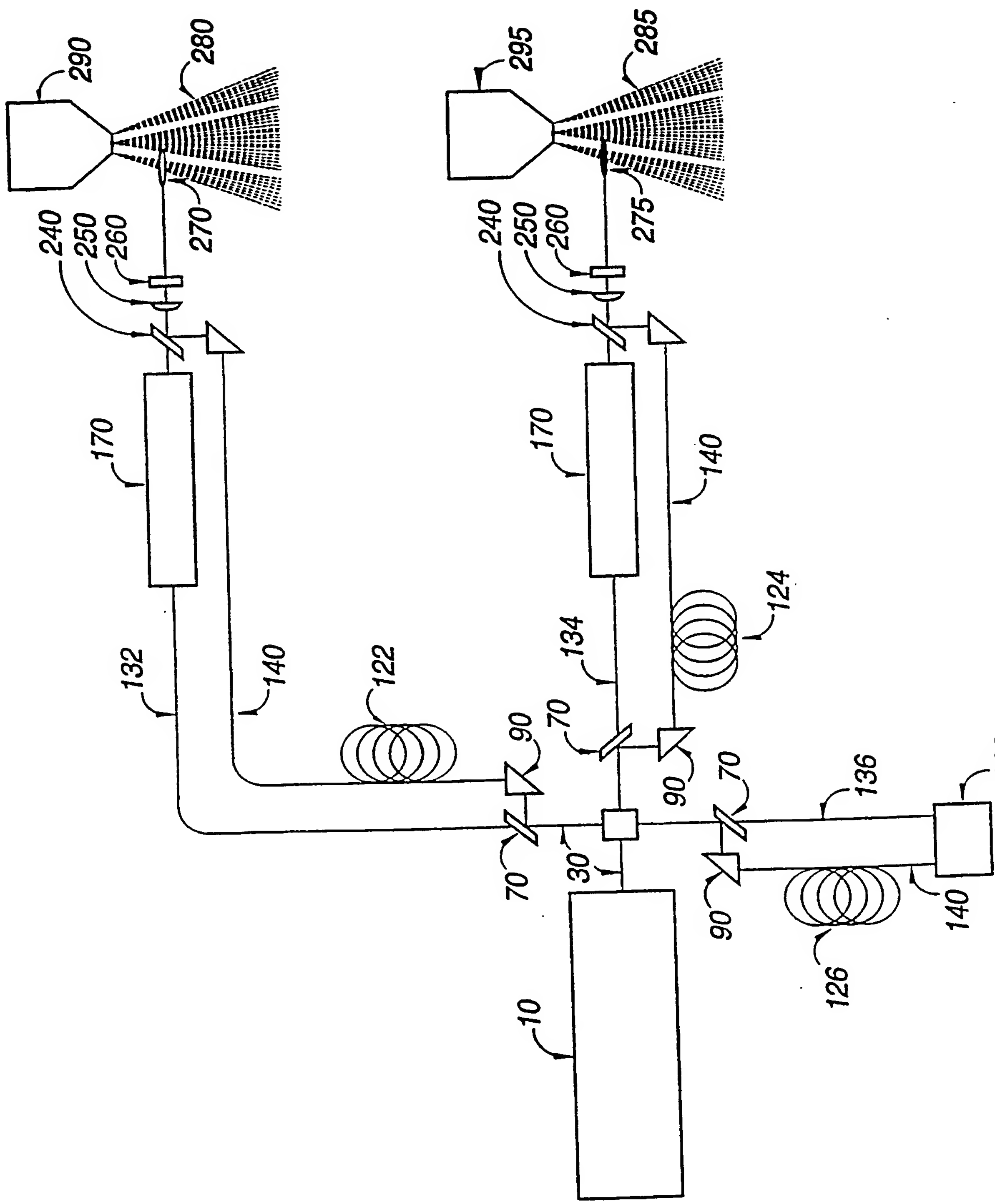
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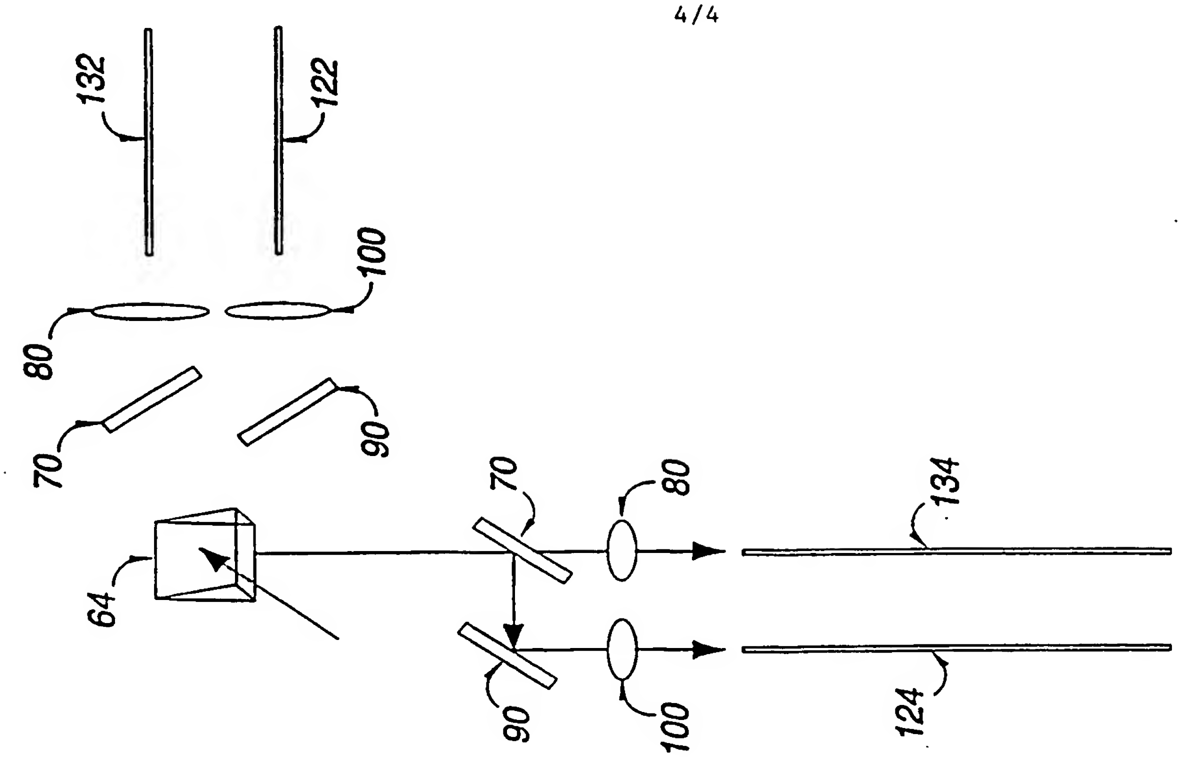
Fig. 3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70
80
134
90
100
124

Fig. 4b

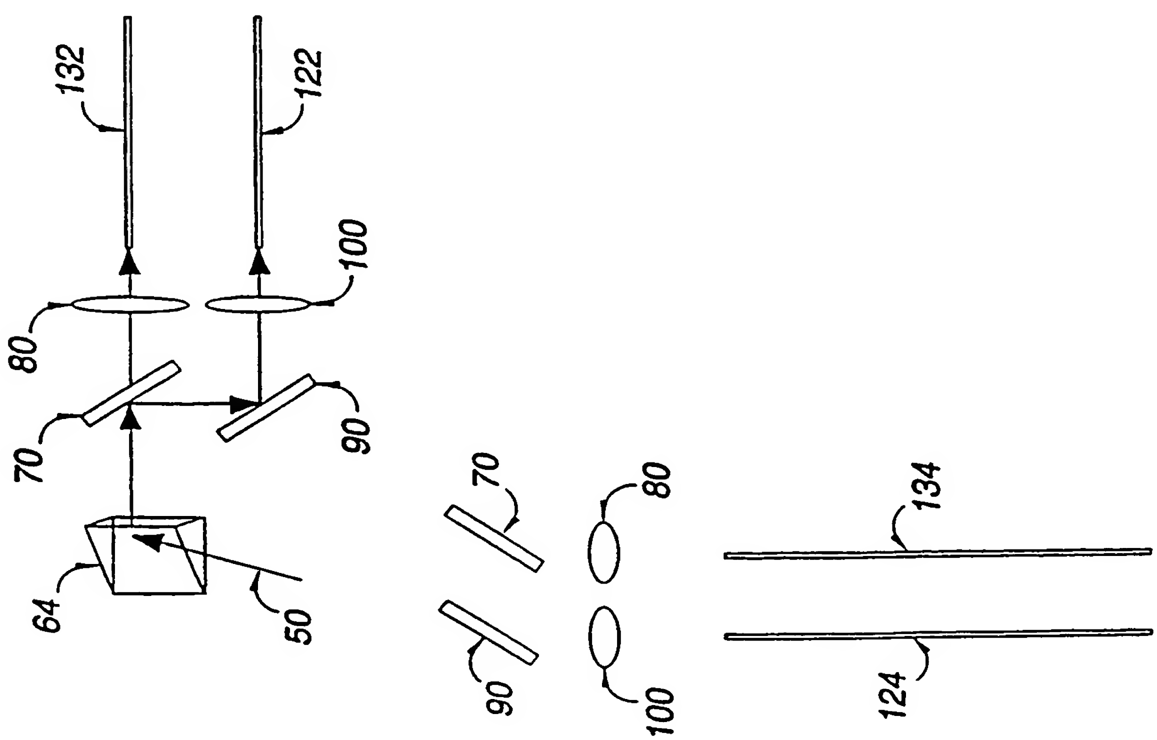
132
122
100
80
70
90
64
50
70
80
134
90
100
124

Fig. 4a

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(71) Applicant: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA [US/US]; Business and Patent Law, Mail Stop D412, Los Alamos, NM 87545 (US).

(71)(72) Applicants and Inventors: EARLY, James, W. [US/US]; 1048 Cedro Court, Los Alamos, NM 87544 (US). LESTER, Charles, S. [US/US]; Route 2, Box 78, San Juan Pueblo, NM 87566 (US).

(74) Agents: BENNETT, Gemma, Morrison et al.; Los Alamos National laboratory, Mail Stop D412, Los Alamos, NM 87545 (US).

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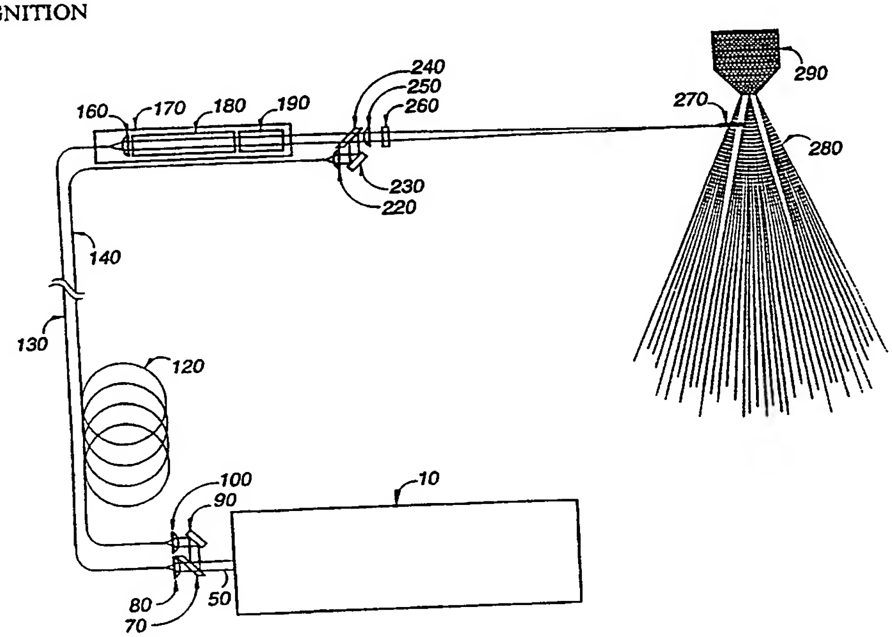

(57)Abstract

In the apparatus of the invention, multiple lasers (10, 170) are used in tandem to provide a compact, durable engine deployable fuel ignition (270, 280) laser system. Reliable fuel ignition is provided over a wide range of fuel conditions by using a first laser (10) as an excitation light source for one (170) or more small lasers (170) located proximate to one (280, 290) or more (280, 290, 285, 295) fuel combustion zones.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/06611

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US CL :431/254
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B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 60/39.06;102/201,202,213;204/157.41;372/29;431/1,2,6,254,256

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3,902,036 A (ZALECKAS) 26 August 1975, see entire document.	1-8
A	US 4,870,244 A (COPLEY et al) 26 September 1989, see figure 2.	1-8
Y	US 4,947,640 A (FEW et al) 14 August 1990, see optical fiber 22, laser 20, lenses 34 and 40, injector 16 and fuel spray 18.	1-2 and 6-8
Y	US 5,157,676 A (WILCOX) 20 October 1992, see entire document.	1-2 and 6-8
A	US 5,367,869 A (DeFREITAS) 29 November 1994, see laser 44, optical cable 46, laser beam 40 and fuel spray 24.	1-8

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Name and mailing address of the ISA/US
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Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer
LARRY JONES
Telephone No. (703) 308-1933